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Application of contemporary engineering techniques and technologies in the field of dental prosthetics

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Analysis and modelling

ABSTRACT

Purpose: During the last couple of decades, development of medical science has been marked with an ever more pronounced interdisciplinary character which, in part, can be attributed to various engineering applications. Rapid development of computer-aided technologies, which completely transformed production engineering, also left an indelible mark on dental prosthetics. Striving towards its primary goal - primum non nocere ('Above all, do not harm!'), the area of dental prosthetics has introduced numerous novel technologies and methods which allow manufacture of precision, custom-made, optimal dental replacements.
Design/methodology/approach: The aim of research - to contribute to integration of modern engineering technologies and computer-aided systems into dental prosthetics with special emphasis on efficient manufacture of dental replacements with precision which allows clinical applicability. The subject scope of the paper comprises modelling, manufacturing with special emphases on materials, quality inspection and environmental impact assessment (cleaner production).
Findings: In the industrially developed countries, efforts have been concentrated towards advancement of modelling and manufacture of dental replacements by introducing modern computer equipment and state-of-the-art materials and machining technologies. However, in countries in transition, dental replacements are predominantly manufactured in a traditional, manual way prone to errors. The reasons for this situation are various.
Practical implications: It is expected that this trend will have a significant impact on the further development of production engineering techniques and technologies in the near future.
Originality/value: The paper evolved on the premise that there is a room for more intensive co-operation between the two disciplines - dental prosthetics and engineering, with a prospect for success of the development of novel, original solutions. In that sense, this paper should serve to both professions – production engineers and dentists.
Keywords: CAD/CAM, CAQ; Manufacturing and processing; Cleaner production

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1. Introduction

During the last couple of decades, development of medical science has been marked with an ever more pronounced interdisciplinary character which, in part, can be attributed to various engineering applications. In that respect, dentistry is a branch of medicine with the longest tradition of incorporating engineering solutions.

Dental prosthetics - the branch of dentistry which deals with the replacement of missing teeth and related mouth or jaw structures by bridges, dentures, or other artificial devices - has always maintained close relationships with engineering disciplines, mostly relying on production engineering. Constant and rapid development of computer-aided technologies, which completely transformed production engineering, also left an indelible mark on dental prosthetics. Striving towards its primary goal - *primum non nocere*, i.e., *"Above all, do not harm!"* the area of dental prosthetics has introduced numerous novel technologies and methods which allow manufacture of precision, custom-made, optimal dental replacements [1,2].

In the industrially developed countries, especially during the last decade, efforts have been concentrated towards advancement of modelling and manufacture of dental replacements by introducing modern computer equipment and state-of-the-art materials and machining technologies, as opposed to traditional way of manual manufacture which is prone to numerous subjective errors. The results are high-quality dental replacements and a more efficient manufacturing process. Amongst the modern engineering technologies, i.e. computer-aided systems which have found broad application in this area, the most widely used are 3D-digitization, CAD, reverse engineering (RE), CAE, CAM, plastic forming, rapid manufacturing (RM), rapid prototyping (RP), Computer Aided Inspection (CAI), computer-aided quality (CAQ), etc. The development and implementation of such technologies and systems have paved the way towards significant advancement of conventional modelling, manufacture and inspection of dental replacements [1-3].

Unfortunately, in countries in transition, dental replacements are predominantly manufactured in a traditional, manual way (Fig. 1) which, in essence, requires manual acquisition of dental imprints and creation of a model which is subsequently used to manufacture a casting mould. Such procedure - especially at the initial stage of dental imprint acquisition and subsequent modelling - largely relies on the skills and daily readiness of a performing dentist. Imprecision which arise at this stage are almost impossible to compensate for at subsequent stages of manufacture. Moreover, the errors accumulate in the process, contributing to emergence of additional errors in the course of manufacturing [1-3].

The reasons for such a situation in dentistry are various. However, the lack of co-operation between researchers and experts from the areas of dental prosthetics and engineering can be marked as the primary culprit.

This paper evolved on the premise that there is a room for more intensive co-operation between the two disciplines with a prospect for success. Presently available human and material resources in production engineering and dentistry provide excellent basis for significant improvements regarding the implementation of state-of-the-art engineering technologies as well as the development of novel, original solutions.

Having in mind the basic stages of modelling and manufacture of dental replacements, in this article special attention is devoted to:

- application of state-of-the-art (contact and optical) systems for intra oral and extra oral 3D-digitization, including systems based on Computer Tomography;
- RE-CAD modelling of virtual dental replacements;
- manufacture of dental replacements by cutting technologies, RP and RM technologies.

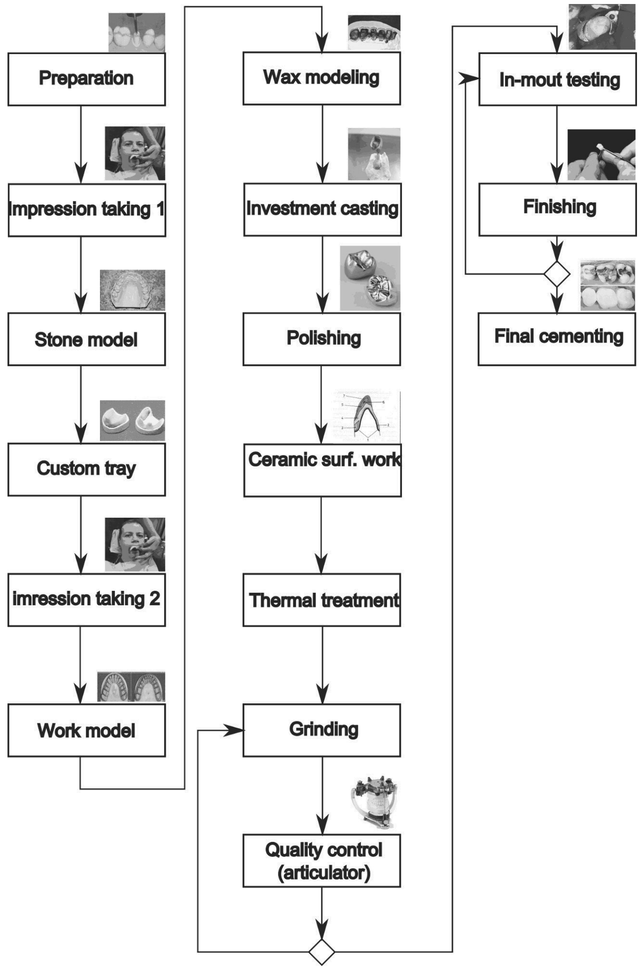

Fig. 1. Workflow of the traditional procedure for modelling and manufacture of dental replacements [3]

2. Modelling of dental replacements

Contemporary approaches of dental restorations' modelling, in general, include:

- 3D digitization and
- virtual design (i.e., RE-CAD modelling).

The mentioned two segments of this process are presented in more detail below.

2.1. 3D digitization

The modelling phase starts with the 3D digitization of the patient's cast. This process can be dual, regarding the applied 3D digitization methodology - extra oral or intra oral.

Application of extra oral 3D digitization systems usualy includes acquiring a dental impression and extra oral scanning of a gypsum model produced from the impression, Fig. 2 [2,3]. However, the need for making impression could be replaced by the application of intra oral scanning or CT, Figs. 3 and 4 [2,4].

Fig. 2. Dental impression, gypsum models and extra oral 3D digitization system *Sirona "InEos Blue"*

Fig. 3. Intra oral scanner *CADENT iTero®*

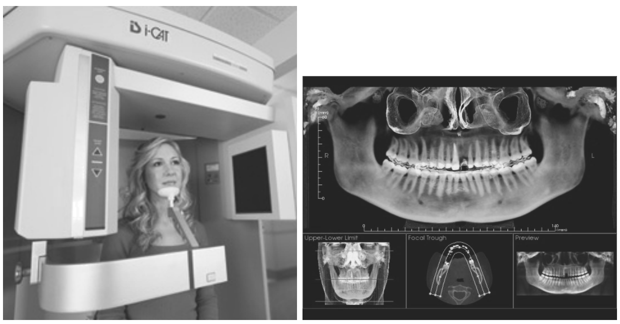

Fig. 4. Dental CT scanner *i-CAT Cone Beam* with software

3D-digitization is one of crucial segments in dental CA technologies. For that reason systems for 3D digitization have been rapidly developed during the last several years. Within this part, the review study on the 3D digitization systems with the application in the field of dental prosthetics is presented. The study was conducted on the basis of available data collected from literature, manufacturers, distributors and direct users of the systems. Analysis was conducted independently for extra oral and intra oral systems, and included specialized dental 3D digitization systems and 3D digitizing systems for more general purposes.

Within extra oral group of 3D digitization systems, three types of systems were analysed:

1) contact systems,
2) noncontact optical systems and
3) noncontact systems based on computed tomography (CT).

The analysis included a total of 9 systems, and the results of the analysis are given in Table 1 [1-8].

Intra oral systems for 3D-digitization in the field of dental prosthetics are intensively developed in recent years and are already recognized as highly applicable and significant in this area. This analysis included six specialized dental systems and one more general-purpose system. Results of the conducted analysis are presented in Table 2 [1-8].

2.2. Virtual design of dental replacements

Computer application in dental prosthetics enabled a replacement of manual by virtual modelling, which today comprises reverse engineering (RE) and CAD modelling techniques. The role of RE-CAD is to generate a virtual working model on the bases of preparation's 3D digitization results, and to design a final virtual model of the desired dental restoration [9-11]. The first systems of this type were highly specialized hardware and software system, exclusively designed for implementation in the field of dental prosthetics, such as e.g. Cerec 1 and Cerec 2. Newer RE-CAD systems are characterized by specialized software components compatible with the operating system software (mostly Windows environments) and the hardware that is PC platforms, such as Cerec 3, Fig. 5 [11-16].

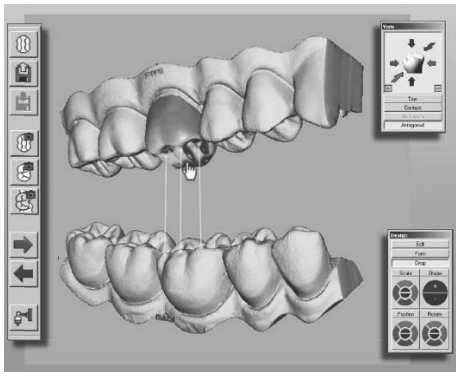

Fig. 5. Interface of RE-CAD software system *Cerec 3*

The virtual design of dental restorations today almost always requires the application of RE modelling. RE, a modelling technique widely used in different engineering fields, has been increasingly applied in the field of prosthodontics during the last several years, mainly because of rapid development of dental 3D digitization systems and corresponding modelling software [9-16].

The point cloud obtained, through the process of 3D digitization, almost always needs to be pre-processed in order to insure a high quality surface reconstruction, i.e., a credible CAD model, Fig. 6. Regarding the applied 3D digitization technique/system, the pre-processing step can include different processes such as noise filtering, data reduction, segmentation of the point cloud parts or assembling [5-7]. The obtained surface model (the reference model or the "buck") is usually exported to an STL file format based on triangular polygons, which is a suitable format for virtual dental surveying and virtual sculpting environments, Fig. 6 [10].

Table 1.
Extra oral system analysis

Feature \ System	Denti Cad, BEGO - Bremen	DSC Precident - Austenal DSC Dental AG	Procera Forte - NobelBiocare	Cerec inEOS	KAVO	Atos III Triple Scan-GOM	MicroScribe G2 Immersion (articulated arm)	Contura G2 Zeiss (CMM)	METROTOM 800 Zeiss (industrial CT)
Specialized / General purpose	*S*	*S*	*S*	*S*	*S*	*G*	*G*	*G*	*G*
System's mobility	●	●	●	●	●	●	●	∅	∅
Contact	●	●	●	∅	∅	∅	●	●	∅
Noncontact	∅	∅	∅	●	●	●	∅	◖	●
Manual / Automated	*M*	*M*	*A*	*A*	*A*	*A*	*M*	*A*	*A*
Internal (invisible) surface digitization	∅	∅	∅	∅	∅	∅	∅	∅	●
Fixturing need	●	●	●	∅	∅	∅	●	●	∅
Sensitivity on surface reflection	∅	∅	∅	●	●	●	∅	∅	∅
Sensitivity on surface hardness	●	●	●	∅	∅	∅	●	●	∅
Sensitivity on material density	∅	∅	∅	∅	∅	∅	∅	∅	●
Speed	▼	▼	►	▲	▲	▲	▼	▼	▲
Measuring uncertainty	/	/	1.7 μm	/	10 μm	/	0.2 mm	1 μm	/
Resolution	/	/	/	/	/	10 μm	/	/	1900 x 1512 pixels
Price	▼	▼	►	►	►	▲	▼	►	▲
Application in practice	►	▼	▲	▲	►	▼	►	►	▼

● - has the feature; ∅ - no feature; ◖ - optional feature; / - unknown (no data); ▼- low; ►- medium; ▲- high

Table 2.
Intra oral system analysis

Feature \ System	CADENT iTERO	Lava COS	Hint-Els	TRIOS	Cerec AC &in Lab - Sirona	3DCT Medica (Cone Beam CT)	CT SENSATION 64 Multyslice - SIEMENS
Specialized / General purpose	S	S	S	S	S	S	O
System's mobility	●	●	●	●	●	●	∅
Contact	∅	∅	∅	∅	∅	∅	∅
Noncontact	●	●	●	●	●	●	●
Image/Video based method	S	V	S	S	S	S	S
Manual / Automated	M	M	M	M	M	A	A
Internal (invisible) surface digitization	∅	∅	∅	∅	∅	●	●
Fixturing need	∅	∅	∅	∅	∅	∅	∅
Sensitivity on surface reflection	●	●	●	●	●	∅	∅
Sensitivity on material density	∅	∅	∅	∅	∅	●	●
Sensitivity on surface hardness	∅	∅	∅	∅	∅	∅	∅
Speed	▲	▲	▲	▲	▲	▲	▲
Measuring uncertainty	/	/	/	/	/	/	/
Resolution	/	/	/	/	0.19 mm	0.1 mm	0.6 mm
Price	►	►	►	►	►	►	▲
Application in practice	▼	►	▼	▼	▲	▼	▼

● - has the feature; ∅ - no feature; ◖ - optional feature; / - unknown (no data); ▼- low; ►- medium; ▲- high

STL model generation is followed by the specific modelling step (or steps) dependent on the dental replacement type (Fig. 6). In the case of removable partial denture (RPD) framework design, the STL model is used for virtual identification of present undercut areas on the CAD model of patient's teeth and soft tissues (Fig. 6). Unwanted undercuts have to be removed in order to ensure unobstructed withdrawal of the RPD from the patient's orifice. This is followed by the reliefs' modelling (the parts of a model that prevent the RPD framework resting on the surfaces of soft tissues - Fig. 7a) as well as the virtual sculpting of RPD framework elements (Fig. 7b) [8,10,17,18].

The revolutionary technique of virtual sculpting is based on software tools enabling analogous work to that used in physical sculpting. This is enabled through a haptic interface that incorporates positioning in 3D space and allows rotation and translation in all axes, transferring hand movements into the virtual environment, Fig. 8. However, the most important feature of haptic system is enabling the operator to feel the contact with the object which is the subject of the modelling. It is important to note that contemporary software for virtual sculpting, along with the usage of the haptic arm allows the application of standard CAD parametric features. This adds to modelling flexibility as well as to higher efficiency [10,17,18].

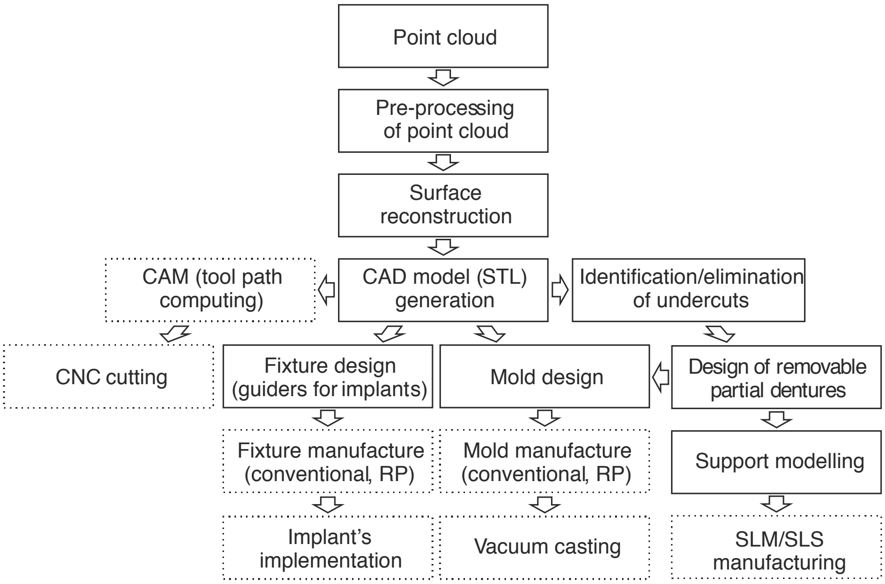

Fig. 6. RE modelling and virtual design steps according to dental replacement types

a) Identified undercuts and modelled reliefs

b) RPD framework elements

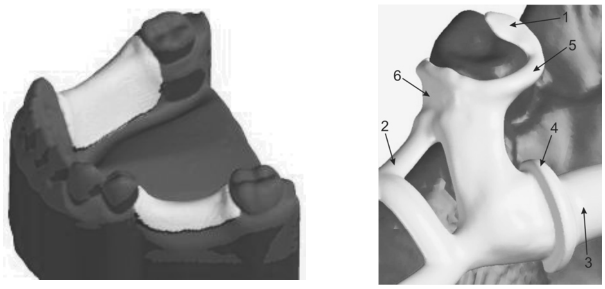

Fig. 7. Modelling of RPD framework [10]

Fig. 8. Virtual sculpting system with haptic arm

3. Manufacture of dental replacements

The classical approach dental restorations' manufacturing involves a lot of manual labour, while the quality directly depends on the skill and experience of dentists and dental technicians. From the production engineering viewpoint, manufacture of dental restorations can be classified as highly complex and individual production. That is why the choice of methodology is reduced to computer aided manufacturing (CAM). In other words, the outcome quality of dental restorations can be greatly increased by the implementation of CAM in the manufacturing process. Technologies applied for dental restorations' manufacturing on the bases of CAM systems, can be divided into following seven groups [15-18]:

- electric discharge machining - EDM (also referred to as spark eroding or wire erosion);
- milling;
- electrophoresis of ceramic materials;
- metal forming technologies;
- additive manufacturing - selective laser melting SLM and selective laser sintering SLS;
- rapid prototyping RP.

The application of EDM in the field of dental prosthetics is of historic importance and was developed in the framework of the Procera® system. Titanium dental caps are made in this way by a combination of milling and EDM technologies.

Milling is the most widely used CAM based technology in the field of dental prosthetics (Fig. 9). The base system consists of the software support (for tool path generation on the bases of the CAD model) and numerically controlled (NC) machine tool. The performances of these systems are determined by the features of machine tools and software support. The linear precision of this technology is approximately 10µm, which is acceptable for the denture. However it should be noted that the overall accuracy depends on all components of a specific system. An important feature of this kind of systems is the cutting speed, i.e. rotation per minute. Processing of the dental ceramic materials requires about 100,000 rotations per minute and diamond cutting tools. Another important feature of a machining system is the number of control axes. The most of machining systems of this type include from 3½ to 5½ control axes [15-18].

a) b)

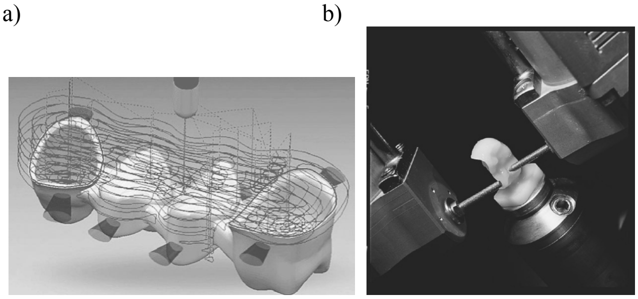

Fig. 9. Simulated tool path in Delcam's dental CAM software (a) and Cerec2 dental machining system in process (b)

Electrophoresis of the ceramic material is a trademark of Wolceram Company. Characteristic of this technology is the need for liquid form of ceramic material. The process of making ceramic crowns is possible due to electro-conductivity of the working preparation's surface.

The application of metal forming technologies is also very common in the production of dental restorations. The most applied metal forming methods in the field of dental prosthetics include: cold extrusion forging, micro-deformation in the cold and hot condition, severe plastic deformation, cold incremental forming, incremental laser-assisted forming, and super-plastic forming [19]. Structure of metal materials is changing during the process of plastic deformation, affecting the changes of mechanical properties. This phenomenon is particularly evident with cold deformation that is conducted at temperatures below the recrystallization temperature. The result is a significant increase of material hardness and strength and decrease of toughness and plastic properties. The phenomenon of strain hardening is important in manufacturing of dental restorations by the application of metal forming technology. However, some materials such as titanium alloys, which belong to the group of biocompatible material, are characterized by low plasticity in the cold, and their shaping must be carried out in heated state or by applying a special method (e.g. hydrostatic forming). Forming of dental restorations from titanium alloys is carried out in the heated state by the application of incremental laser-assisted forming (Fig. 10), super plastic forming (Fig. 11) and forging [19-21].

Additive manufacturing is the newest method for dental restorations' manufacture, based on coalescence of fine particulate material - metal (Au, Ti, Co-Cr-Mo) or ceramic with the help of laser heat. Particle size range from 0.005 to 0.045 mm. The energy of laser melts (selective laser melting - SLM) or sinters (selective laser sintering - SLS) the material powder to create thin layers, with the thickness of around 0.075 mm (Fig. 12) [8,10,22]. The procedure is time demanding but it is however possible to manufacture tenths of replacements at the same time and to compensate the time spent (Fig. 13). As there is almost no excess of used material with this technology it is very profitable for application with expensive materials [23-26].

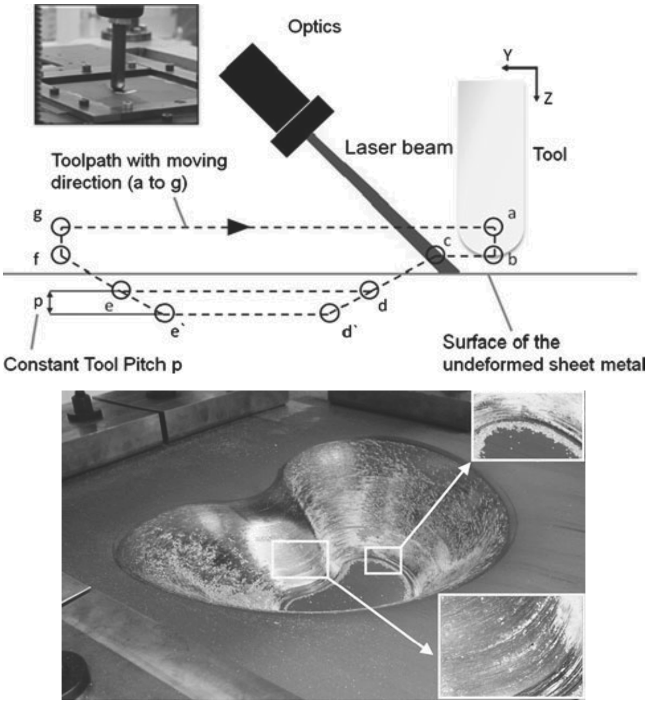

Fig. 10. Application of incremental laser-assisted forming in manufacturing of dental restorations

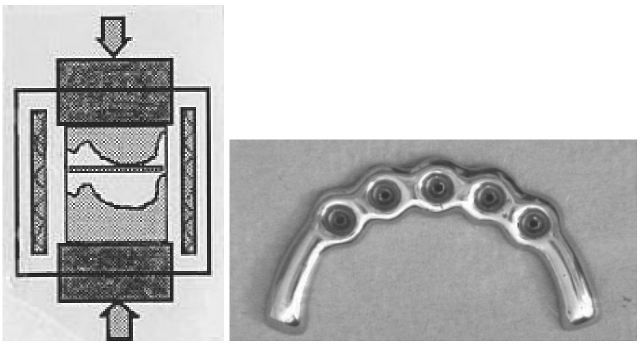

Fig. 11. Application of super plastic forming in manufacturing of dental restorations

When speaking about additive technologies in the field of dental prosthetics, it is important to mention rapid prototyping (RP) methods that are increasingly used in developed countries in this field. The reasons for this lay in the fact that RP technology, combined with the RE modelling, allows the creation of dental restorations that are tailored to individual patient requirements. The typical field of RP application in this area today is manufacture of moulds for precision casting of Co-Cr-Mo alloys, as well as for manufacture of guiders for implants positioning, Fig. 14 [28-32].

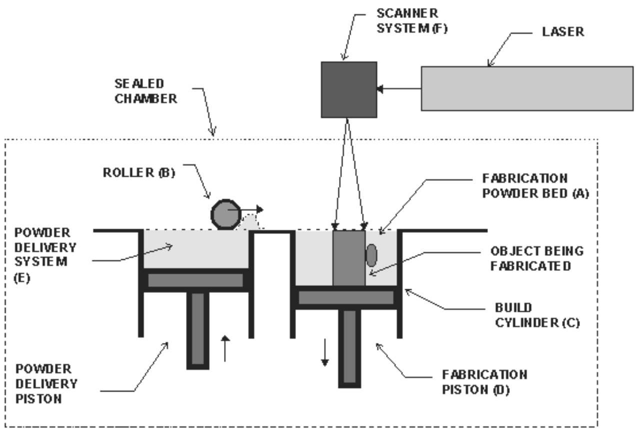

Fig. 12. Selective laser sintering methodology

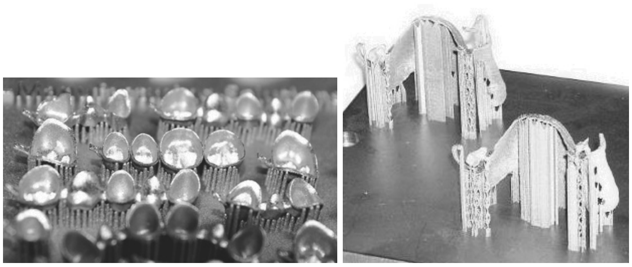

Fig. 13. Additive manufacturing of dental caps (a) and removable partial dentures (b)

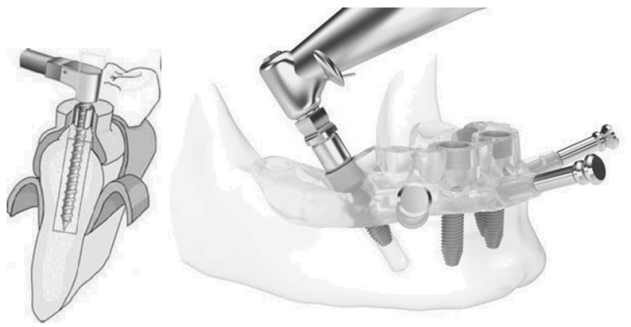

Fig. 14. RP guiders for positioning of dental implants

4. Conclusions

This paper provides an overview of engineering techniques and technologies, primarily from the field of production engineering, which are applied in the field of dental prosthetics. Based on the foregoing review, it can be concluded that the application of these techniques and technologies is very intense and broad in terms of application of different methods and technologies. Furthermore, it can be concluded that the use of presented technologies significantly influenced the development of dental prosthetics, both in terms of improving the effectiveness of the processes of modelling and manufacture of dental restorations, as well as in terms of overall quality of dental restorations, i.e. benefits for patients. It is expected that this trend will have a significant impact on the further development of production engineering techniques and technologies in the near future.

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